中山大學
SUN YAT-SEN UNIVERSITY
计算机学院（软件学院）
SCHOOL OF COMPUTER SCIENCE AND ENGINEERING

Compilation Principle
编 译 原 理

第17讲：语义分析(3)

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Review Questions

- What are S-SDD and L-SDD?

  S-SDD: synthesized-SDD (only syn attributes),
  L-SDD: left-attributed SDD (only left-to-right dependency).

- For S-SDD, how to get the SDT?

  Place all semantic actions at the end of productions.

- For L-SDD, how to get the SDT?

  Syn, the end of production; inh, right before the occurrence.

- Why S-SDD is natural to be implemented in LR parsing?

  Syn attributes: evaluate parent after seeing all children (=reduce).

- Why L-SDD is not natural for LR parsing?

  Semantic actions can be in anywhere of the production body.

L-SDD in LL Parsing[非递归预测]

- Extend the parse stack to hold **records** and certain **data items** needed for attribute evaluation[扩展语法分析栈]
  - Action-record[动作记录]: represent the actions to be executed
  - Synthesize-record[综合记录]: hold synthesized attrs for non-terminals
  - Typically, the data items are copies of attributes[属性备份]
- Manage attributes on the stack[管理属性信息]
  - The inherited attributes of a nonterminal *A* are placed in the stack record that represents that terminal[符号位放继承属性]
    - Action-record to evaluate these attributes are immediately above *A*
  - The synthesized attributes of a nonterminal *A* are placed in a separate synthesize-record that is immediately below *A*[综合属性另存放]

action	Code
A	Inh Attr.
A.syn	Syn Attr.

Example

(1) T -> F { T'.*inh* = F.*val* } T' { T.*val* = T'.*syn* }

(2) T' -> * F { T_1'.*inh* = T'.*inh* x F.*val* } T_1' { T'.*syn* = T_1'.*syn* }

(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }

Three kinds of symbols:
1) terminal
2) non-terminal
3) action

(1) T -> F { a_1 } T' { a_2 } (2) T' -> * F { a_3 } T_1' { a_4 } (3) T' -> ε { a_5 } (4) F -> digit { a_6 }	a_1: T'.*inh* = F.*val* a_2: T.*val* = T'.*syn* a_3: T_1'.*inh* = T'.*inh* x F.*val* a_4: T'.*syn* = T_1'.*syn* a_5: T'.*syn* = T'.*inh* a_6: F.*val* = digit.*lexval*

Example (cont.)

(1) T -> F { a_1 } T' { a_2 }	a_1: T'.*inh* = F.*val* a_2: T.*val* = T'.*syn*
(2) T' -> * F { a_3 } T_1' { a_4 }	a_3: T_1'.*inh* = T'.*inh* x F.*val* a_4: T'.*syn* = T_1'.*syn*
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action	Code
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Input: 3 * 5

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- 变量展开时（i.e., 变量本身的记录出栈时），若其含有继承属性，则要将继承属性复制给后面的动作记录
- 综合记录出栈时，要将综合属性值复制给后面的动作记录

完整步骤见👉： MOOC:语法制导翻译-3

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T	Tsyn	$
	val	

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https://www.icourse163.org/learn/HIT-1002123007

Example (cont.)

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F	Fsyn	{ a_1 }	T'	T'syn	{ a_2 }	Tsyn	$
	val		inh	val		val	

完整步骤见👉：MOOC:语法制导翻译-3

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Fsyn	{ a_1 }	T'	T'syn	{ a_2 }	Tsyn	$
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digit	{ a_6 }	Fsyn	{ a_1 }	T'	T'syn	{ a_2 }	Tsyn	$
lexv=3		val		inh	val		val	

完整步骤见👉： MOOC:语法制导翻译-3

Example (cont.)

(1) T -> F { a_1 } T' { a_2 }	a_1: T'.*inh* = F.*val* a_2: T.*val* = T'.*syn*
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digit	{ a_6 }	Fsyn	{ a_1 }	T'	T'syn	{ a_2 }	Tsyn	$
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digit	{ a_6 }	Fsyn	{ a_1 }	T'	T'syn	{ a_2 }	Tsyn	$
lexv=3	d_lexv=3	val		inh	val		val	

完整步骤见👉： MOOC:语法制导翻译-3

Example (cont.)

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完整步骤见👉： MOOC:语法制导翻译-3

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Stack top 'digit' matches the input '3'
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a_6: stack[top-1].*val* = stack[top].*d_lexval*

{ a_6 }	Fsyn	{ a_1 }	T'	T'syn	{ a_2 }	Tsyn	$
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- 变量展开时（i.e., 变量本身的记录出栈时），若其含有继承属性，则要将继承属性复制给后面的动作记录
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- pop 'digit', but value copy is needed

a_6: stack[top-1].*val* = stack[top].*d_lexval*

{ a_1 }	T'	T'syn	{ a_2 }	Tsyn	$
val=3	inh	val		val	

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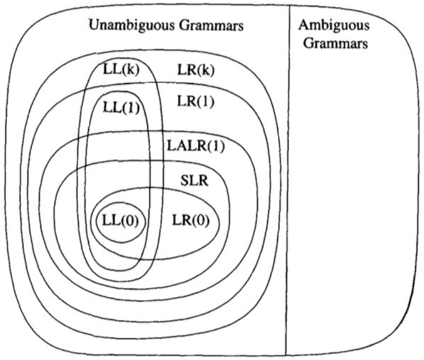
完整步骤见👉：MOOC:语法制导翻译-3

L-SDD in LR Parsing[LR解析]



- What we already learnt
  - LR > LL, w.r.t parsing power
    - We can do bottom-up every translation that we can do top-down[所有的LL都可以LR]
  - S-attributed SDD can be implemented in bottom-up way
    - All semantic actions are at the end of productions (triggered in reduce)
- For L-attributed SDD on an LL grammar, can it be implemented during bottom-up parsing?
  - Problem: semantic actions can be in anywhere of the production body

(1) T -> F { T'.*inh* = F.*val* } T' { T.*val* = T'.*syn* }
(2) T' -> * F { T_1'.*inh* = T'.*inh* x F.*val* } T_1' { T'.*syn* = T_1'.*syn* }
(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }

The Problem

- It is not natural to evaluate inherited attributes
  - Example: how to get T'.*inh*

(1) T -> F { T'.*inh* = F.*val* } T' { T.*val* = T'.*syn* }
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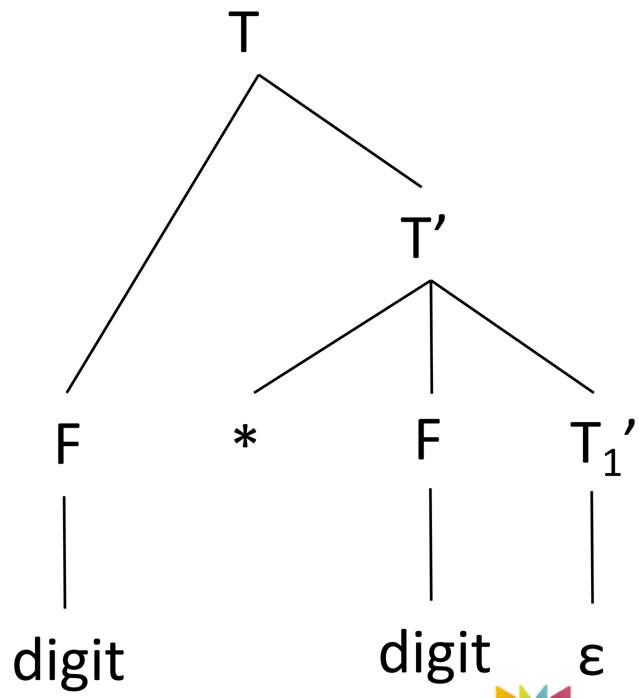

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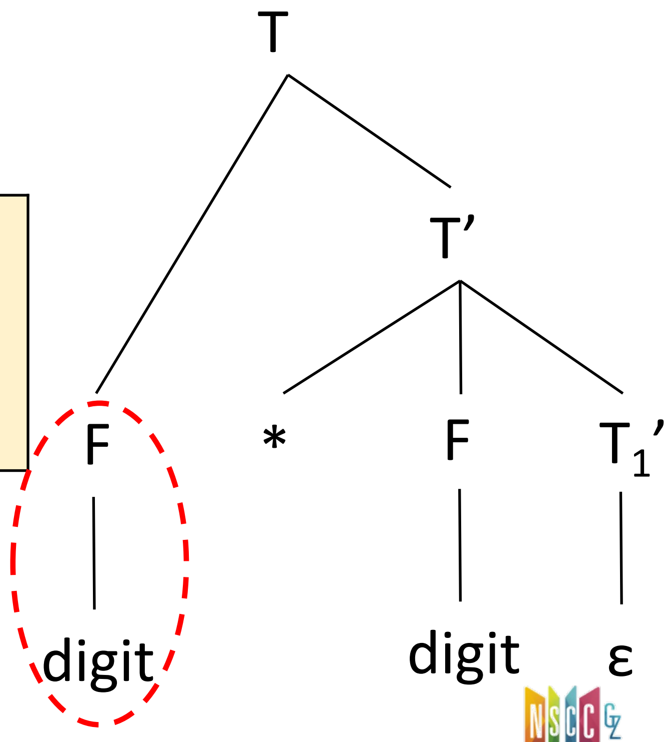

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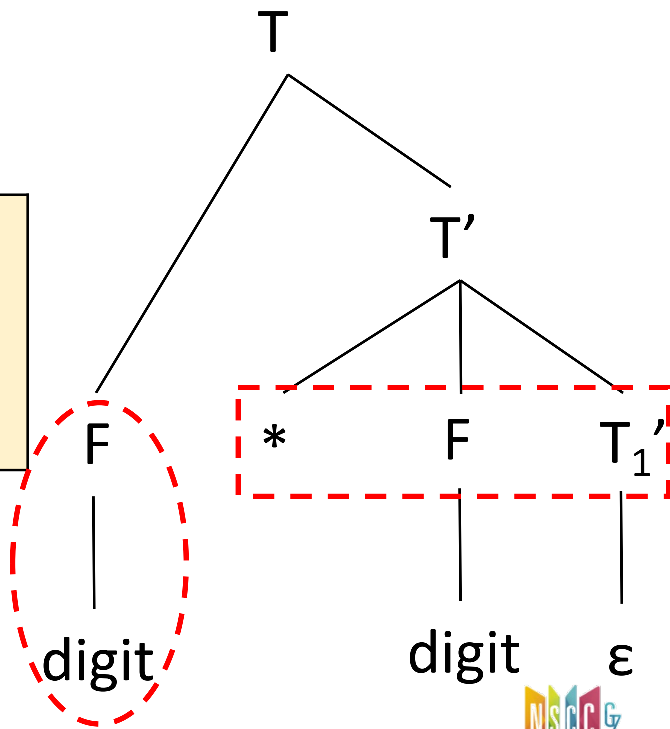

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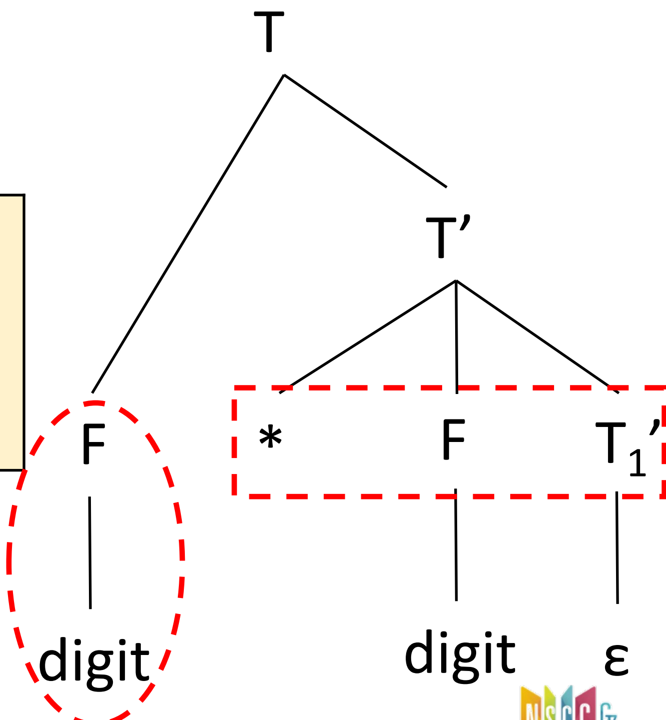

The Problem

- It is not natural to evaluate inherited attributes
  - Example: how to get T’.*inh*
- Claim: inherited attributes are on the stack
  - Left attributes guarantee they’ve already been computed
  - But computed by previous productions – deep in the stack
- Solution
  - **Hack the stack to dig out those values**

(1) T -> F { T’.*inh* = F.*val* } T’ { T.*val* = T’.*syn* }
(2) T’ -> * F { T_1’.*inh* = T’.*inh* x F.*val* } T_1’ { T’.*syn* = T_1’.*syn* }
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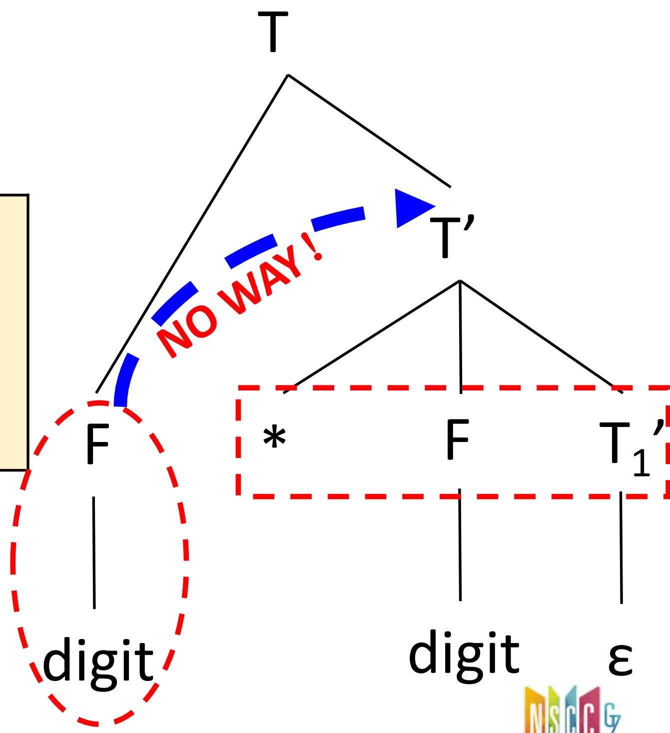
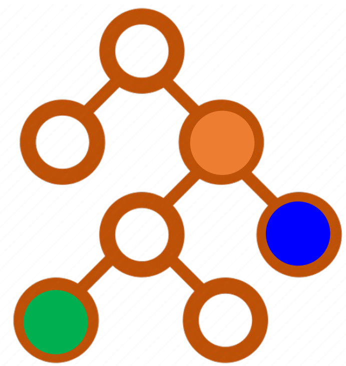


Marker[标记符号]

- Given the following SDD, where |α| ≠ |β|

  A -> X α { Y.*in* = X.*s* } Y | X β { Y.*in* = X.*s* } Y

  Y -> γ { Y.*s* = f(Y.*in*) }



- Problem: cannot generate stack location for Y.*in*
  - Because X.*s* is at different relative stack locations from Y
- Solution: insert markers M_1, M_2 right before Y

  A -> X α M_1 Y | X β M_2 Y

  Y -> γ { Y.*s* = f(stack[top -|γ|].*s*) } // Y.*s* = M_1.*s* or Y.*s* = M_2.*s*

  M_1 -> ε { M_1.*s* = stack[top -|α|].*s* } // M_1.*s* = X.*s*

  M_2 -> ε { M_2.*s* = stack[top -|β|].*s* } // M_2.*s* = X.*s*

  } 分别计算

- **Marker**: a non-terminal marking a location equidistant from the symbol that has an inherited attribute
  - Always produces ε since its only a placeholder for an action

Modify Grammar with Marker[文法修改]

- Given an L-SDD on an LL grammar, we can adapt the grammar to compute the same SDD during a LR parsing
  - Introduce into the grammar a **marker nonterminal**[标记非终结符] in place of each embedded action
    - Each such place gets a distinct marker, and there is one production for any marker *M*, *M* -> ε[空产生式]
  - Modify the action *a* if marker nonterminal *M* replaces it in some production *A* -> α { *a* } β, and associate with *M* -> ε an action *a*' that
    - Copies, as inherited attrs of *M*, any attrs of *A* or symbols of α that action *a* needs (e.g., *M*.*i* = *A*.*i*)[左侧]
    - Computes attrs in the same way as *a*, but makes those attrs be synthesized attrs of *M* (e.g., *M*.*s* = f(*M*.*i*))

A -> { B.*i* = f(A.*i*); } B C

A -> M B C
M -> ε { M.*i* = A.*i*; M.*s* = f(M.*i*); }

Example

(1) T -> F { T'.*inh* = F.*val* } T' { T.*val* = T'.*syn* }
(2) T' -> * F { T_1'.*inh* = T'.*inh* x F.*val* } T_1' { T'.*syn* = T_1'.*syn* }
(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }

(1) T -> F **M** T' { T.*val* = T'.*syn* }
M -> ε { M.*i* = F.*val*; M.*s* = M.*i* }
(2) T' -> * F **N** T_1' { T'.*syn* = T_1'.*syn* }
N -> ε { N.i_1 = T'.*inh*; N.i_2 = F.*val*; N.*s* = N.i_1 x N.i_2 }
(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }

Stack Manipulation[栈操作]

(1) T -> F { T'.*inh* = F.*val* } T' { T.*val* = T'.*syn* }
(2) T' -> * F { T_1'.*inh* = T'.*inh* x F.*val* } T_1' { T'.*syn* = T_1'.*syn* }
(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }

(1) T -> F **M** T' { T.*val* = T'.*syn* }
  M -> ε { M.*i* = F.*val*; M.*s* = M.*i* }
(2) T' -> * F **N** T_1' { T'.*syn* = T_1'.*syn* }
  N -> ε { N.i_1 = T'.*inh*; N.i_2 = F.*val*; N.*s* = N.i_1 x N.i_2 }
(3) T' -> ε { T'.*syn* = T'.*inh* }
(4) F -> digit { F.*val* = digit.*lexval* }

(1) T -> F **M** T' { stack[top-2].*val* = stack[top].*syn*; top = top - 2; }
  M -> ε { stack[top+1].*T'inh* = stack[top].*val*; top = top + 1; }
(2) T' -> * F **N** T_1' { stack[top-3].*syn* = stack[top].*syn*; top = top -3; }
  N -> ε { stack[top+1].*T'inh* = stack[top-2].*T'inh* x stack[top].*val*; top = top + 1; }
(3) T' -> ε { stack[top+1].*syn* = stack[top].T'*inh*; top = top + 1; }
(4) F -> digit { stack[top].*val* = stack[top].*lexval*; }

Example: Inherited Attribute[继承]

SDD:

Production Rules	**Semantic Rules**
(1) D -> T L	L.*inh* = T.*type*
(2) T -> int	T.*type* = int
(3) T -> float	T.*type* = float
(4) L -> L_1, id	L_1.*inh* = L.*inh* addtype(id.*entry*, L.*inh*)
(5) L -> id	addtype(id.*entry*, L.*inh*)

T has synthesized attribute *type*

L has inherited attribute *inh*

Pointing to a symbol-table[符号表] object

Variable declaration of type int/float followed by a list of IDs:

(1) Declaration: a type *T* followed by a list of *L* identifiers
(2) Evaluate the synthesized attribute *T.type* (int)
(3) Evaluate the synthesized attribute *T.type* (float)
(4) Pass down type, and add type to symbol table entry for the identifier
(5) Add type to symbol table

Compilation Phases

- Lexical analysis[词法分析]
  - Source code → tokens
  - Detects inputs with illegal tokens
  - Is the input program lexically well-formed?
- Syntax analysis[语法分析]
  - Tokens → parse tree or abstract syntax tree (AST)
  - Detects inputs with incorrect structure
  - Is the input program syntactically well-formed?
- Semantic analysis[语义分析]
  - AST → (modified) AST + **symbol table**
  - Detects semantic errors (errors in meaning)
  - Does the input program has a well-defined meaning?

Overview of Symbol Table[符号表]

- **Symbol table** records info of each symbol name in a program[符号表记录每个符号的信息]
  - symbol = name = identifier
- Symbol table is created in the semantic analysis phase[语义分析阶段创建]
  - Because it is not until the semantic analysis phase that enough info is known about a name to describe it
- But, many compilers set up a table at lexical analysis time for the various variables in the program[词法分析阶段准备]
  - And fill in info about the symbol later during semantic analysis when more information about the variable is known[语法分析阶段填充]
- Symbol table is used in code generation to output assembler directives of the appropriate size & type[后续代码生成阶段使用]

Variable[程序变量]

- What are **variables** in a program?
  - Variables are the names you give to computer memory locations which are used to store values in a computer program
  - Retrieve and update the variables using the names
- Variable **declaration** and **definition**[声明和定义]
  - Declaration: informs the compiler type and name of a variable[类型和名字]
  - Definition: tells the compiler where and how much storage to create for the variable[内存空间分配]

```
// Variable declarations
extern int x, y;
extern float z;

// Variable definitions
int x, y;
float z;
```


https://www.tutorialspoint.com/cplusplus/cpp_variable_types.htm

Example

```c
#include <stdio.h>

int g_val;

int main() {
    int l_val;
    static int s_val;

    printf("g_val=%d, l_val=%d, s_val=%d\n", g_val, l_val, s_val);

    return 0;
}
```

```
[xianwei@test>]$ gcc -Wall -g -o testc testc.c
testc.c:9:52: warning: variable 'l_val' is uninitialized when used here [-Wuninitialized]
   printf("g_val=%d, l_val=%d, s_val=%d\n", g_val, l_val, s_val);
                                                   ^~~~~
testc.c:6:13: note: initialize the variable 'l_val' to silence this warning
   int l_val;
            ^
             = 0
1 warning generated.
[xianwei@test>]$ ./testc
g_val=0, l_val=282353718, s_val=0
[xianwei@test>]$ ./testc
g_val=0, l_val=142671926, s_val=0
[xianwei@test>]$ ./testc
g_val=0, l_val=227987510, s_val=0
```

https://en.cppreference.com/w/c/language/storage_class_specifiers

https://www.learncpp.com/cpp-tutorial/uninitialized-variables-and-undefined-behavior/

Binding[绑定]

- **Binding**: match identifier use with definition[使用-定义]
  - Definition: associating an *id* with a memory location
  - Hence, binding associates an *id* use with a location
  - Binding is an essential step before machine code generation
- If there are multiple definitions, which one to use?

```
void foo()
{
    char x;     /* allocated at mem[0x100] */
    ...
    {
        int x;  /* allocated at mem[0x200] */
        ...
    }
    x = x + 1;  /* add mem[0x100],1 ? add mem[0x200],1 ? */
}
```

Scope[作用域]

- **Scope**: program region where a definition can be bound
  - Uses of identifier in the scope is bound to that definition
  - For C: auto/local, static, global

- Some properties of scopes
  - Use not in scope of any definition results in undefined errors
  - Scopes for the same identifier can never overlap
    - There is at most one binding at any given time

- Two types: static scoping and dynamic scoping
  - Depending on how scopes are formed

Static Scoping[静态作用域]

- Scopes formed by where definitions are in program text[程序文本就有作用域信息]
  - Also known as lexical scoping since related to program text C/C++, Java, Python, JavaScript[也叫词法作用域]
- Rule: bind to the closest enclosing definition[最近闭合定义]

```
void foo()
{
    char x;
    ...
    {
        int x;
        ...
    }
    x = x + 1;
}
```

Dynamic Scoping[动态作用域]

- Scopes formed by when definitions happen during runtime[运行时决定]
  - Perl, Bash, LISP, Scheme
- Rule: bind to most recent definition in <u>current execution</u>

```
void foo()
{
   (1) char x;
   (2) if (...) {
   (3)     int x;
   (4)     ...
           }
   (5) x = x + 1;
 }
```

- Which *x*'s definition is the most recent?
  - Execution (a): ...(1)...(2)...(5)
  - Execution (b): ...(1)...(2)...(3)...(4)...(5)

Static vs. Dynamic Scoping[对比]

- Most languages that started with dynamic scoping (LISP, Scheme, Perl) added static scoping afterwards

- Why? With dynamic scoping ...
  - All bindings are done at execution time
  - Hard to figure out by eyeballing, for both compiler and human
- Pros of static scoping[静态的好处]
  - Static scoping leads to fewer programmer errors
    - Bindings readily apparent from lexical structure of code
  - Static scoping leads to more efficient code
    - Compiler can determine bindings at compile time
    - Compiler can translate identifier directly to memory location
    - Results in generation of efficient code
- We will discuss <u>static scoping only</u>

Symbol Table[符号表]

- **Symbol**: same thing as **identifier** (used interchangeably)
- **Symbol table**: a compiler data structure tracking info about all program symbols
  - Each entry represents a definition of that identifier
  - Maintains list of definitions that reach current program point
  - List updated whenever scopes are entered or exited
  - Used to perform binding of identifier uses at current point
  - Built by either...
    - Traversing the parse tree in a separate pass after parsing
    - Using semantic actions as an integral part of parsing pass
- Usually discarded after generating executable binary
  - Machine code instructions no longer contain symbols
  - For use in debuggers, symbol tables may be included
    - To display symbol names instead of addresses in debuggers
    - For GCC, using 'gcc -g ..." includes debug symbol tables

Maintaining Symbol Table[维护]

- Basic idea

  int x=0; ... void foo() { int x=0; ... x=x+1; } ... x=x+1 ...

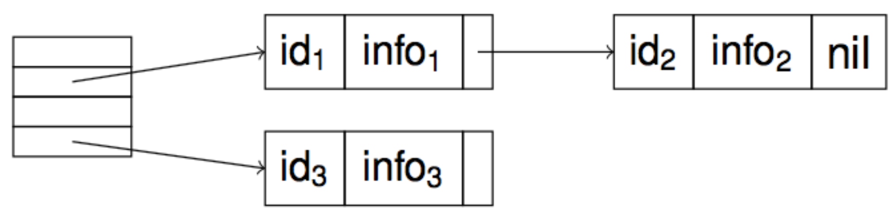
  - Start processing *foo*:
    - Add definition of x, overriding old definition of x if any
  - After processing *foo*:
    - Remove definition of x, restoring old definition of x if any

- Operations
  - enter_scope() start a new scope
  - exit_scope() exit current scope
  - find_symbol(*x*) find the information about *x*
  - add_symbol(*x*) add a symbol *x* to the symbol table
  - check_symbol(*x*) true if *x* is defined in current scope

Symbol Table Structure[结构]

- Frontend time affected by symbol table access time[符号表访问时间影响编译前端性能]
  - Frontend: lexical, syntax, semantic analyses
  - Frequent searches on any large data structure is expensive
  - Symbol table design is important for compiler performance

- What data structure to choose?[可选数据结构]
  - **List**[线性表]
  - **Binary tree**[二叉树]
  - **Hash table**[哈希表]



- Tradeoffs: time vs. space[空间和时间的权衡]
  - Most compilers choose hash table for its quick access time

Adding Scope to Symbol Table[作用域]

- To handle multiple scopes in a program,[处理多个作用域]
  - Conceptually, need an individual table for each scope
    - In order to be able to enter and exit scopes
- Sometimes symbols in scope can be discarded on exit:

```
if (...) { int v; } /* block scope */
/* v is no longer valid */
```

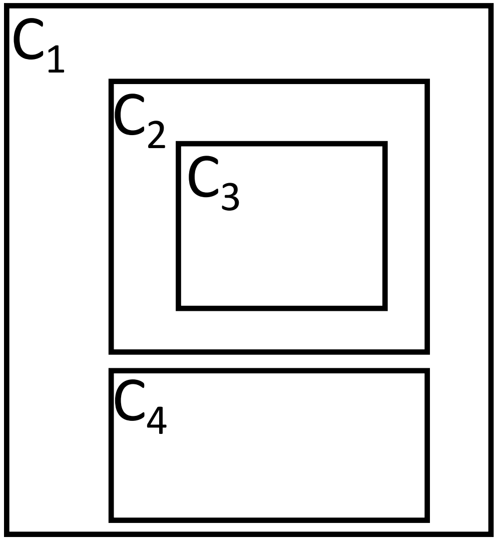
- Sometimes not:

```
class X { ... void foo() {...} ... } /* class scope */
/* foo() is no longer valid */
X v;
call v.foo(); /* v.foo() is still valid */
```

- How can scoping be enforced without discarding symbols?
  - Keep a *stack* of active scopes at a given point
  - Keep a *list* of all reachable scopes in the entire program

Handle Scopes with Stack

- Organize all symbol tables into a scope stack[作用域栈]
  - An individual symbol table for each scope
    - Scope is defined by nested lexical structure, e.g., {C_1 {C_2 {C_3}} {C_4}}
  - Stack holds one entry for each open scope
    - Innermost scope is stored at the top of the stack
- Stack push/pop happen when entering/exiting a scope



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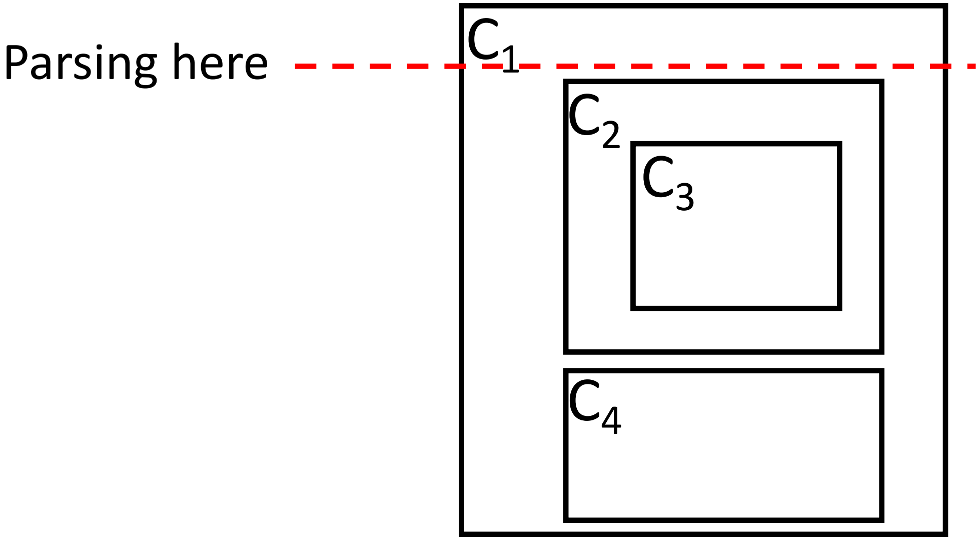

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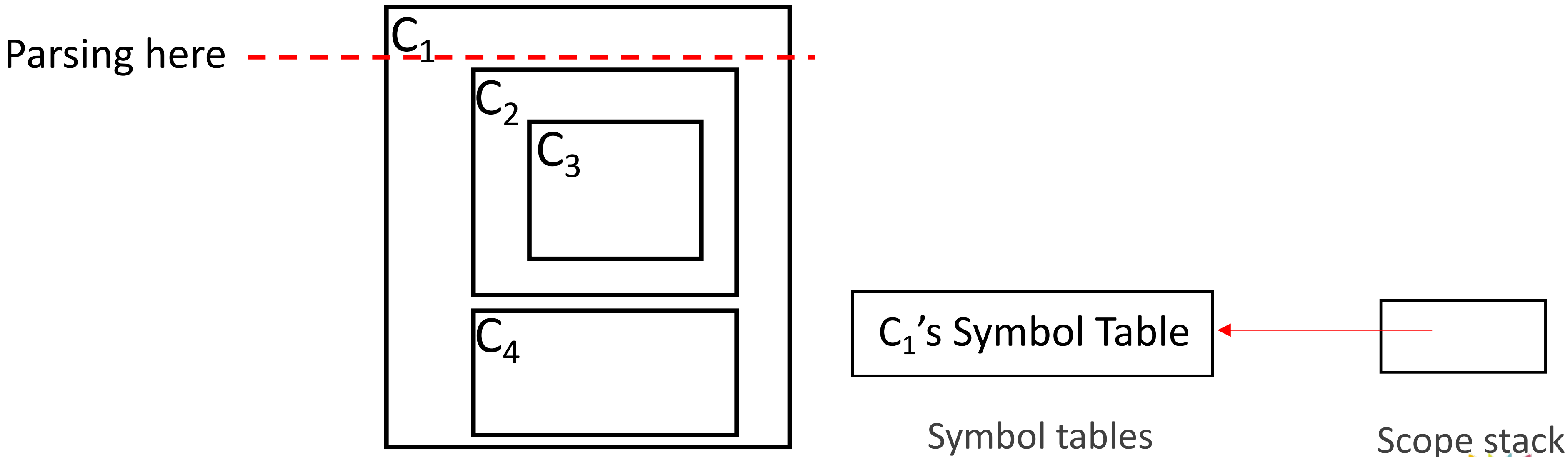
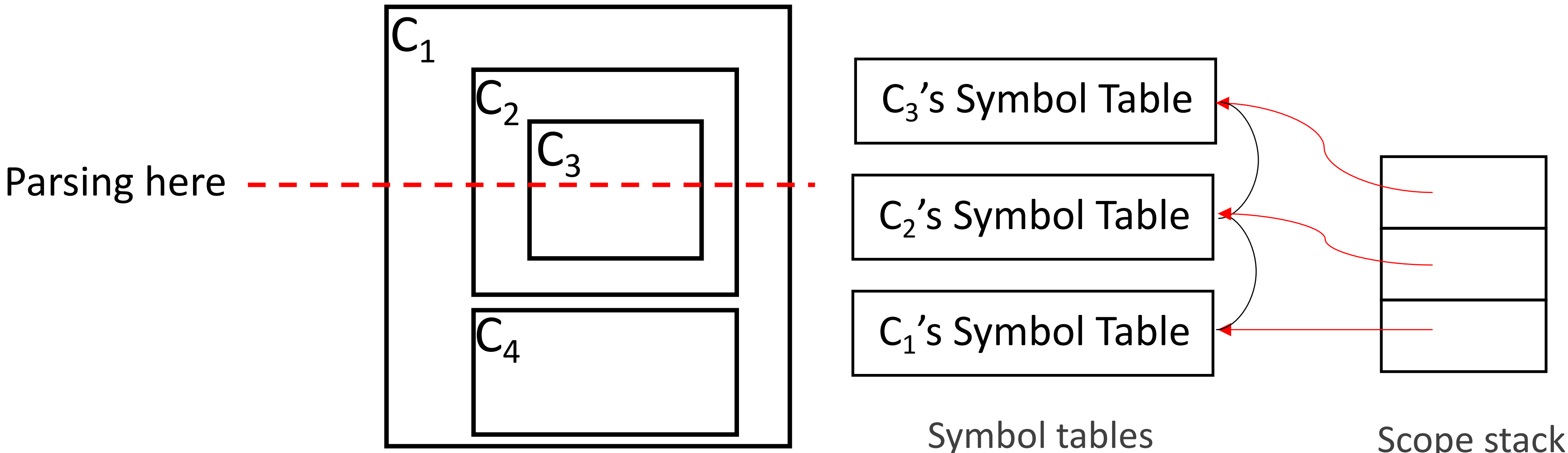


Handle Scopes with Stack (cont.)

- Operations
  - When entering a scope
    - Create a new symbol table to hold all variables declared in that scope
    - Push a pointer to the symbol table on the stack
  - Pop the pointer to the symbol table when exiting scope
  - Search from the top of the stack



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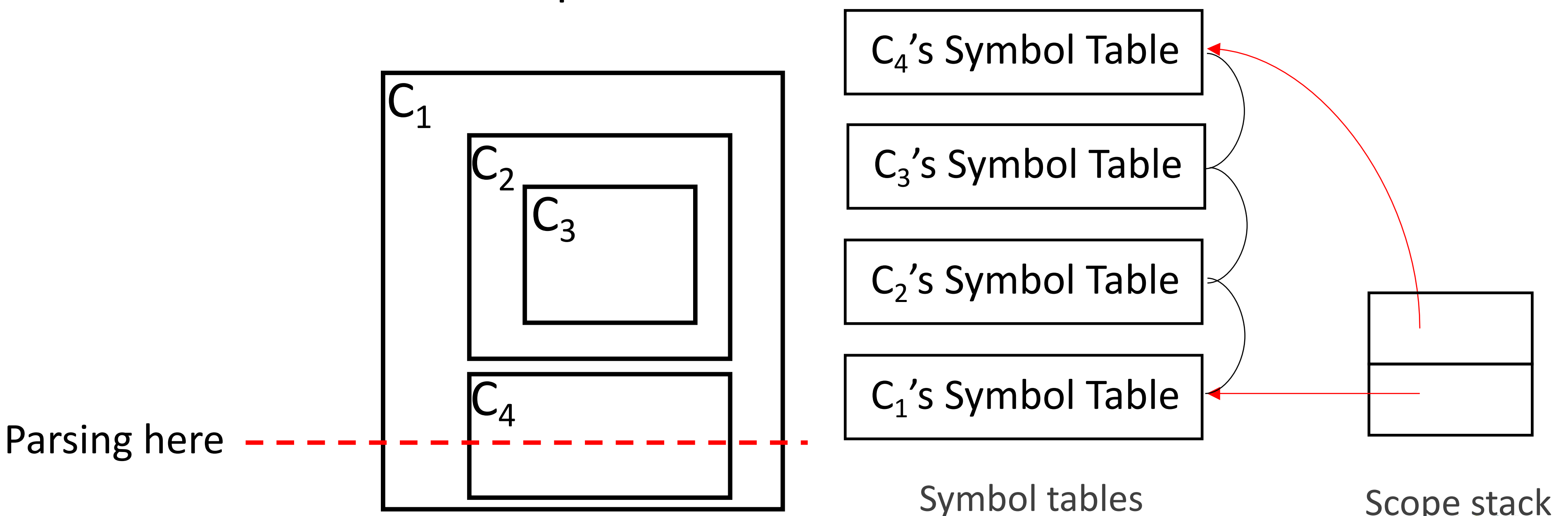
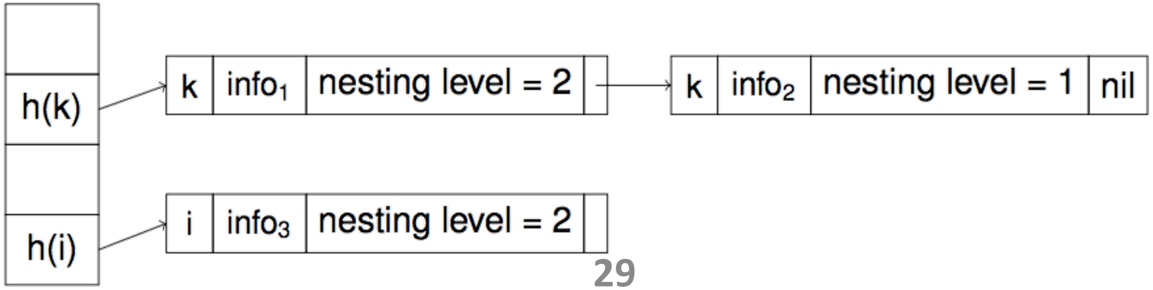


Handle Scopes using Chaining

- Cons of stacking symbol tables[栈方式的缺点]
  - Inefficient searching due to multiple hash table lookups
    - All global variables will be at the bottom of the stack
  - Inefficient use of memory due to multiple hash tables
    - Must size hash tables for max anticipated size of scope
- Solution: single symbol table for all scopes using chaining
  - Insert: insert *(ID, current nesting level)* at front of chain
  - Search: fetch ID at the front of chain
  - Delete: when exiting level *k*, remove all symbols with level *k*
    - For efficient deletion, IDs for each level maintained in a list



Handle Scopes using Chaining (cont.)

- Note: symbol table only maintains currently active scopes
  - All entries with the closing scope are deleted upon exiting
- Note: does not maintain list of all reachable scopes
  - Cannot refer back to old scopes that have been exited
  - Still useful for block scopes that are discarded on exit
- Usages
  - Unsuitable for class scopes (only block scopes)[✗]
  - Exiting scopes is slightly more expensive[✗]
    - Requires traversing the entire symbol table
  - Lookup requires only a single hash table access[✓]
  - Savings in memory due to single large hash table[✓]

Info Stored in Symbol Table

- Entry in symbol table
  - string: the name of identifier
  - kind: function, variable, struct type, class type

string	kind	attributes

- Attributes vary with the kind of symbols
  - variable: type, address of variable
  - function: prototype, address of function body
  - struct type: field names, field types
  - class type: symbol table for class

Attribute List in Symbol Table

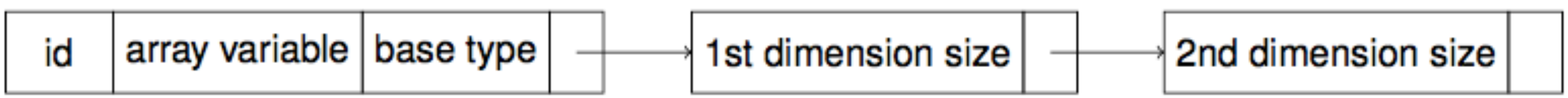
- Type info can be arbitrarily complicated
  - Type can be an array with multiple dimensions

```
char arr[20][20];
```

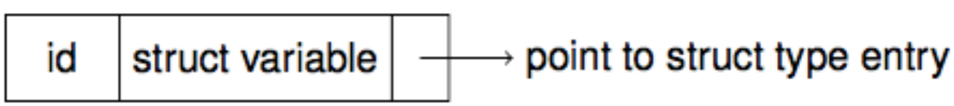
  - Type can be a struct with multiple fields

```
struct Point {
        float x;
        float y;
    } point;
```

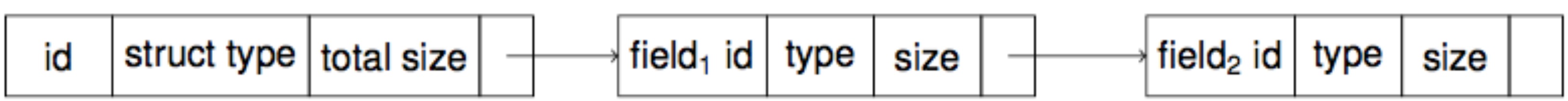
- Store all type info in an attribute list
  - Entry for an array variable with 2 dimensions



  - Entry for a struct variable



  - Entry for a struct type with 2 fields



Use Type Information[类型信息]

- Each variable or function entry contains type info
- Type info is used in later code generation stage[代码生成]
  - To calculate how much memory to alloc for a variable
  - To translate uses of variables to machine instructions
    - Should a '+' on variable be an integer or a floating point add? (fadd/add)
    - Should a variable assignment be a 4 byte or 8 byte copy?
  - To translate calls to functions to machine instructions
    - What are the types of arguments passed to the function?
    - What is the type of value returned by the function?
- Also used in later code optimization stage[代码优化]
  - To help compiler understand semantics of program
- Also used in semantic analysis stage for ***Type Checking***
  - Uses types to check semantic correctness of program

Type and Type Checking

- **Type**: a set of values + a set of operations on these values
  - int/double: same memory storage[类型是语言定义的，而非内存存]
- **Type checking**: verifying type consistency across program[类型一致性检查]
  - A program is said to be type consistent if all operators are consistent with the operand value types
  - Much of what we do in semantic analysis is type checking
- Some type checking examples:
  - Given char *str = “Hello”;
    - str[2] is consistent: char* type allows [] operator
    - str/2 is not: char* type does not allow / operator
  - Given int pi = 3;
    - pi/2 is consistent: int type allows / operator
    - pi=3.14 is not: = operator not allowed on different types
      - Compiler must type convert implicitly to make it consistent

Static Type Checking[静态类型检查]

- Static type checking: at compile time[静态：编译时]
  - Infers program is type consistent through code analysis
    - Collect info via declarations and store in symbol table
    - Check the types involved in each operation
  - E.g., int a, b, c; a = b + c; can be proven type consistent because the addition of two *int*s is an *int*

- Difficult for a language to only do static type checking
  - Some type errors usually cannot be detected at compile time
    - E.g., a and b are of type *int*, a * b may not in the valid range of *int*
    - Typecasting can be pretty risky thing to do (basically, typecast suspends type checking)
      - unsigned a; (int)a;

Dynamic Type Checking[动态检查]

- Dynamic type checking: at execution time[动态：执行时]
  - Type consistency by checking types of runtime values
  - Include type info for each data location at runtime
    - E.g., a variable of type double would contain both the actual double value and some kind of tag indicating “double type”
    - The execution of any operation begins by first checking these type tags
    - The operation is performed only if everything checks out (otherwise, a type error occurs and usually halts execution)
  - E.g., C++/Java downcasting to a subclass
    - Is `dynamic_cast<Child*>(parent);` type consistent?
  - Array bounds check:
    - Is `int A[10], i; … A[i] = i;` type consistent?
- Static type checking is always more desirable. Why?
  - Always good to catch more errors before runtime
  - Dynamic type checking carries runtime overhead

Static vs. Dynamic Typing[静态-动态]

- Static typing: C/C++, Java, …
  - Variables have static types → hold only one type of value
    - E.g. int x; → x can only hold ints
    - E.g. char *x; → x can only hold char pointers
  - How are types assigned to variables?
    - C/C++, Java: types are explicitly defined
    - int x; → explicit assignment of type int to x
- Pros / cons of static typing
  - More programmer effort
    - Programmer must adhere to strict type rules
    - Defining advanced types can be quite complex (e.g. classes)
  - Less program bugs and execution time
    - Thanks to static type checking

Static vs. Dynamic Typing (cont.)

- Dynamic Typing: Python, JavaScript, PHP, ...
  - Variables have dynamic types → can hold multiple types

```
var x; /* var declaration without a static type */
x = 1; /* now x holds an integer value */
x = "one"; /* now x holds a string value */
```

  - How are types assigned to variables?
    - Type is a runtime property → type tags stored with values
    - Dynamic type checking must be done during runtime
- Pros / cons of dynamic typing
  - Less programmer effort
    - Flexible type rule means program is more malleable
    - Absence of types / classes declarations means shorter code
    - Makes it suitable for scripting or prototyping languages
  - More program bugs and execution time
    - Due to dynamic type checking

Type System[类型系统]

- Static / dynamic typing are type systems
  - **Type System**: types + type rules of a language
- Static / dynamic type checking are methods
  - Methods to enforce the rules of the given type system
- Static type checking is not used exclusively for static typing[静态类型检查也会被动态系统使用]
  - Static type checking also used for dynamic typing
  - If certain types can be inferred and checked at compile time
    - Can reduce dynamic type checks inserted into code
- Dynamic type checking is not used only for dynamic typing[动态类型检查也会被静态系统使用]
  - Some features of statically typed languages require it
    - e.g. downcasting requires type check of object type tag

Type Systems: Soundness, Completeness

- Static type checking through inference
  - Inference: deducing a conclusion[结论] from a set of premises[前提]
  - What are the premises? Type rules in the type system
  - What is the conclusion? Accept / reject after applying rules
- A type system is said to be *Sound[可靠]* if:
  - Only correct programs are accepted[只接受正确程序]
  - Flipside: all incorrect programs are rejected[拒绝所有错误程序]
- A type system is said to be *Complete[完备]* if:
  - All correct programs are accepted[接受所有正确程序]
  - Flipside: only incorrect programs are rejected[只拒绝错误程序]
- A type system strives to be both sound and complete
  - The rules of inference (type rules) should reflect that

Rules of Inference

- What are rules of inference?
  - Inference rules have the form

    if *Precondition* is true, then *Conclusion* is true
  - Below concise notation used to express above statement

    $$\frac{\text{Precondition}}{\text{Conclusion}}$$
  - For example: Given E3 → E1 + E2, a rule may be:

    if E1, E2 are type consistent and *int* types (*Precondition*),

    then E3 is type consistent and is an *int* type (*Conclusion*)
- Recursive type checking via inference
  - Start from variable and constant types at bottom of tree
    - Serves as initial preconditions for the inference
  - Apply rules on operator nodes while working up the tree
    - Checks type consistency and assigns type to node

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